LONGEVITY OF CD MEDIA
RESEARCH AT THE LIBRARY OF CONGRESS

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Abstract

Progress in ongoing investigations into the aging of both CD-ROM (mostly audio) and CD-R and RW (rewritable) media under accelerated as well as natural aging conditions is described. Results obtained over the past seven years from a pilot project to monitor the condition of the CD collection at the Library of Congress under real-life use, or natural aging environments are presented. Also presented is a preliminary plan and early observations of an accelerated aging study of CDs (ROM and rewritable) media that is currently in an early stage of development.

The goal of this research is to gain a better understanding of the stability and failure mechanisms of CDs in order to be able to 1) provide the best long-term protection for our collections, 2) establish relevant parameters for monitoring CDs to indicate when creating backup copies or migration of data may be necessary, and 3) identify the most stable CDs for long term preservation purposes. This paper addresses CDs and not DVDs.

Background

The Library of Congress has long been committed to gain an understanding in which optical storage media ages and fails, since optical media by its nature and design lends itself to long-term storage applications, being robust, not subject to wear, and not easily damaged by use.

The earliest studies at the Library date back to accelerated aging studies with 12-inch optical WORM discs during the mid eighties and early nineties. Accelerated aging were to demonstrate the Arrhenius aging methodology and determine the end of life of the discs in question. The test procedures were developed in a standard described in reference 1. AIIM, with NIST support, later developed error monitoring scheme for the WORM, MO, and the CD optical media as described in reference 2 and 3. These tests involved placing the discs in an elevated temperature and humidity environment typically for repeated periods of 500 to 2000 hours to accelerate potential chemical changes that may affect the operational characteristics of the discs. About that time, IT9, an ANSI standard committee, was developing life expectance procedures for optical media and came up with three documents, dealing with CD-ROM, CD-R, and MO media. The standard for CD-ROM is described in reference 4, while similar documents are available for the CD-R and the MO media.

Current Research

There are two basic research agendas: one, to look at the condition of our CD current collection and develop a metric to monitor its condition or state; and two, to perform accelerated aging studies to define and understand the changes in the various measurable parameters in order to determine failure modes and specify life expectancies of various CDs.

This paper focuses first and mostly on the natural aging of the Library's existing CD-ROM, mostly audio, collection; and some initial findings of the on going accelerated aging studies dealing with both ROMs and re-writable CDs.

Natural Aging Study

In 1996, the CD-Audio collection at the Library of Congress was estimated to contain over 60,000 titles. This was just a verbal estimate form a curator, and estimates now are over 150,000, another verbal estimate. It is the intent of the Library to keep these discs forever. Using destruction accelerated testing would not be an acceptable test procedure to determine the life expectancy of these discs. But still it is important to know the condition of these collections and attempt to understand the failure processes. To this end, a CD-Audio testing and monitoring program was initiated. It was intended at that time that this be an on-going activity, periodically sampling the collection to determine if any changes have occurred to the measured parameters. With such information, and with information from the accelerated aging test data, projections could be made as to the condition or "health" of the CD-Audio collection.

Initially a limited number of CDs, a sample size of 125, were selected from our general collection and monitored over an extended time. The object was to observe how or if defects or errors would occur in these CDs under normal storage and use conditions. This project was initiated in 1996 as the base-line sampling of date, and repeated twice since, once in 1999 and again in 2003. At that time it was though that the size of the sample could be increased to about one thousand to perhaps give a better statistical representation of the entire collection. The collection does not represent a uniform distribution, so an increase in the sample size to 1000 CDs may still not be adequate.

Figure 1. represents the 125 discs in terms of their copyright date or production right date. This date, in all cases may not be the exact manufactured date, but it is the best date associated with the given CD.

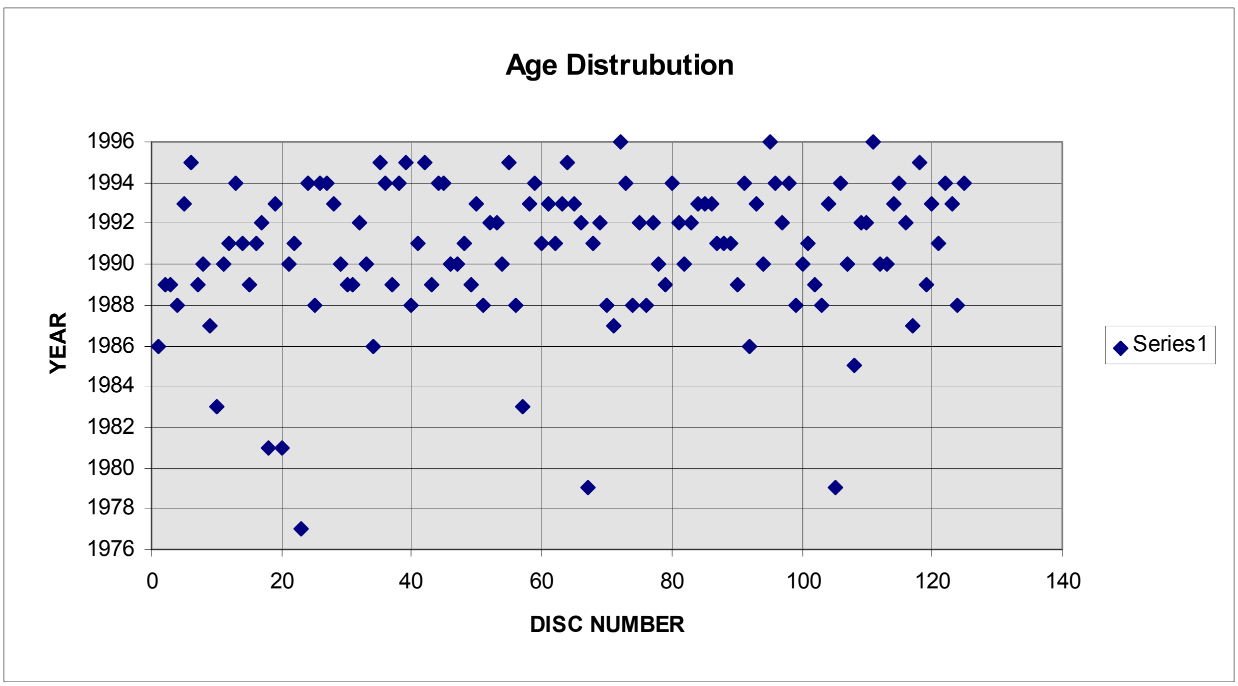

Figure 1. Approximate Age Distribution of Sample.

For all practical purposes we can assume that this sample does represent the age distribution of the CD collection at the time, 1996. Obviously many CDs have been added to the collection since, and therefore, it seems intuitive that a similar study should be repeated to represent the current CD collection. But this sample was selected in 1996 and monitored ever since. The monitoring may be continued to get a "Run 4", sometime after the 2005 time frame.

A specialized tester, the CD-CATS/SA3, reference 5, designed specifically for CDs according to the Philips Red / Blue / Green / Orange Book standards, ISO9660 and extensions, reference 6. This tester measures 25 parameters according to the physical specification of CDs as defined in ISO 10149, reference 7. In addition to the ISO specifications the tester measures jitter and effect of length deviation, based upon production level requirements Phillips and Sony. Reference 5 defines these parameters along with the ISO documents. It is generally accepted that these measurements and statistics are important indicators of CD operability. Appendix defines the acronyms in a summarized form for each of the parameters.

The test results are grouped by the CD CATS system into three data categories: static data, dynamic data, and the recommended length deviation and jitter data. Definitions can be found in references 5 and 7.

BLER, E32, and jitter are perhaps the three most widely used indicators of errors or problems, although many other parameters will give an indication that something is happening. In essence, all parameters are tracked.

The tester also generates an "OUT OF SPEC. LIST", based on the maximum or minimum values specified for each parameter by the user of the CD CATS system, a useful reporting mechanism for flagging or monitoring levels or errors. An out of specification level does not necessary indicate an error, it depends on the parameter and where on the disc the error occurred. For example, the "error" may not be data related.

The selected sample population was first subjected to testing in 1996 to establish the baseline test parameters for each CD in the sample population. Since then, the full range of testing was repeated in 1999, Run2, and again in 2003, Run3. Since a minimum of 3 points is needed to project a trend, this is our first endeavor in this direction.

Examination of the Test Data

All test parameters were collected from the CD-CATS system for each of the 125 CDs in the test. All CDs were run at X1 speed and 100% sampling was used. To date three successive tests were conducted, baseline, run2 and run3. The importance is the change from baseline rather than absolute value. Absolute value may be from preconditions or from manufacturer's process, and our concern is natural aging. All errors were tabulated and used to draw references to other errors, such as the correlation between BLER and E32. Also of interest are the parameters that change with time. A disc may be manufactured with certain errors on a particular part of a particular track that will show up as an error, but will have no effect on the playability or reading any of the useful data. Therefore, before any judgment can be made as to an "error", the specific measurement needs to be carefully examined as to where it occurred and what other parameters indicated an error at the same time.

It is common knowledge that the technology of the manufacture of CDs has undergone extensive improvement over the years. Therefore, it is most interesting to note that for disc number 23, which has a associative date of 1977, the BLER remained relatively constant during the three test runs, being 36, 34, and 36. Likewise, disc numbers 66 and 105, both of which also date back to the late 1970's, exhibited little change is the BLER.

BLER is often considered an adequate indicator as to the condition of the disc. Often there is a correlation between BLER and some of the other test parameters mentioned above, but sometimes there are unexplainable exceptions to this fact. A scatter plot of the BLER for the baseline run of the sample of 125 discs is Figure 2 below. Scatter plots for Run2 and Run3 follow in Figure 3 and Figure 4.

BLER obviously is not the only parameter to consider. Scatter plots are available for all parameters and correlation between parameters can be made. Also, relationships between parameters can be made for a particular disc where for example the BLER may be high, but the E32 low, or where the BLER and E32 occurred at about the same time. Surface presentation can be used to locate where on the disc errors occurred. These types of analysis were conducted, but because of the sheer volume of data generated, these are not included here.

Three scatter plots covering the years 1996, 1999, and 2003 give some indication of trends. Keep in mind that this sample consists of CDs that were all manufactured prior to 1997. Much has happened since that time. Production techniques have improved and most noticeable is the lower BLER reading associated with current CDs.

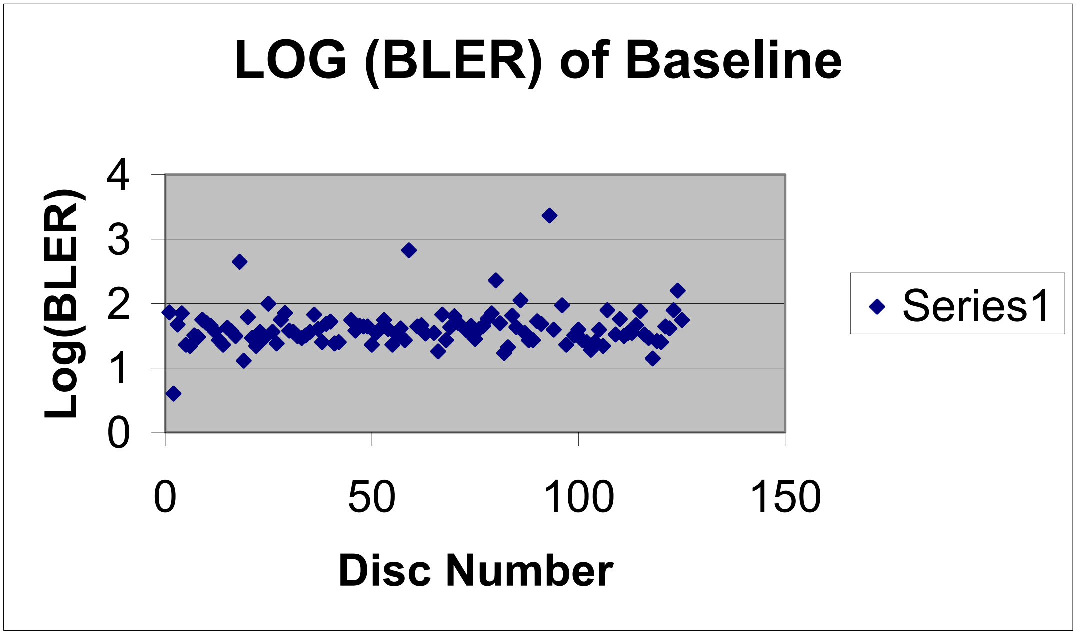

Figure 2. Plot of Log BLER at baseline (1996 data).

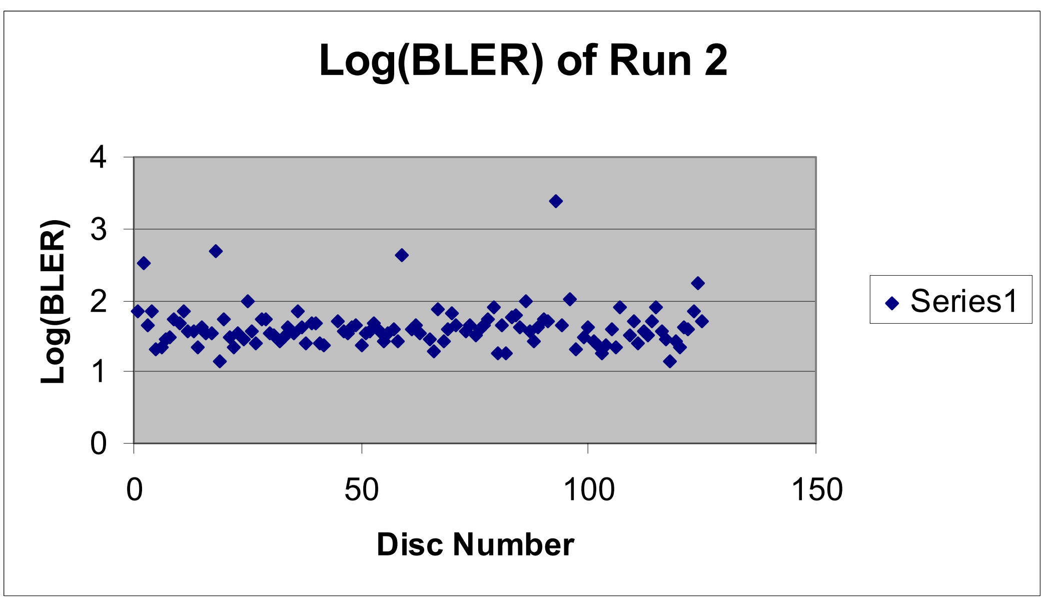

Figure 3. Plot of Log BLER at Run 2, (1999 data).

Four discs had a BLER greater than the maximum rate of 220, log(220) is about 2.34. These discs are numbered 18, 59, 80, and 93. These same discs also exhibited E32 errors, fatal uncorrectable errors. However, there was no noticeable audio defect in the recording. These discs continued to show these results in subsequent runs as seen below.

Figures 3 shows the results after Run 2. Note for disc number 2, the BLER went from 4 to 355, while for disc number 80 the BLER went from 228 to 18. It is difficult to explain this except to say there may be some instrumental errors in reading the BLER. Other parameters for this disc remained about the same or normal for a typical measurement. Discs numbered 18, 59, and 93 showed little change and were all in excess of the standard limit for all three runs. Discs numbered 18 and 59 had readings of BLER in the mid 400's while disc number 93 had a BLER in the range of 2300.

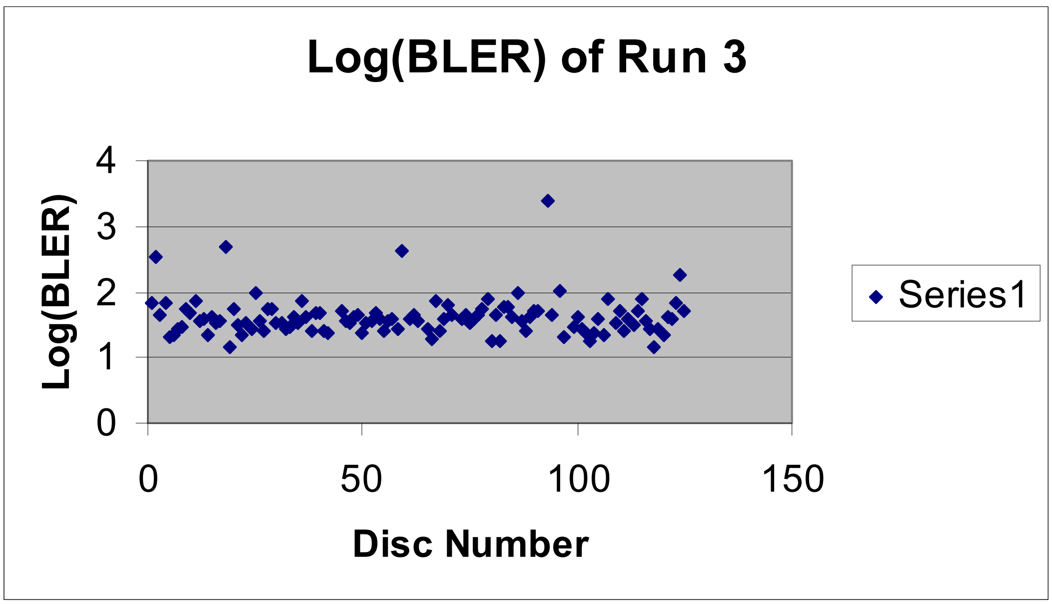

Figure 4. Plot of Log BLER after Run #3, (2003 data).

The BLER by themselves to not reveal any significant variations from successive runs, except for disc 2 and disc 80. These could be measurements errors as the CD-CATS sometimes generates a number out of character. This is being investigated. Figure 5, below, shows an average BLER for the entire sample for each of the three runs. Average BLER is meaningless, since we do not have a uniformity in the sample, discs are made by different manufacturers, dates, and sample had no controlled environmental history. However, within a given sample and using the same equipment and measurement techniques, the data does indicate a drift.

Other parameters to consider and analyzed include normalized reflectivity. The scatter plot for this property was fairly flat and only two CDs were out of specification for reflectivity. However, these two CDs did not have any E32 errors and the BLER were within specification, suggesting that these reflectivity "errors" were not significant, but worth observing for later runs. There are different ways of calculating this parameter and it is often an indication of surface dirt or scratches, which will not always result in a fatal error.

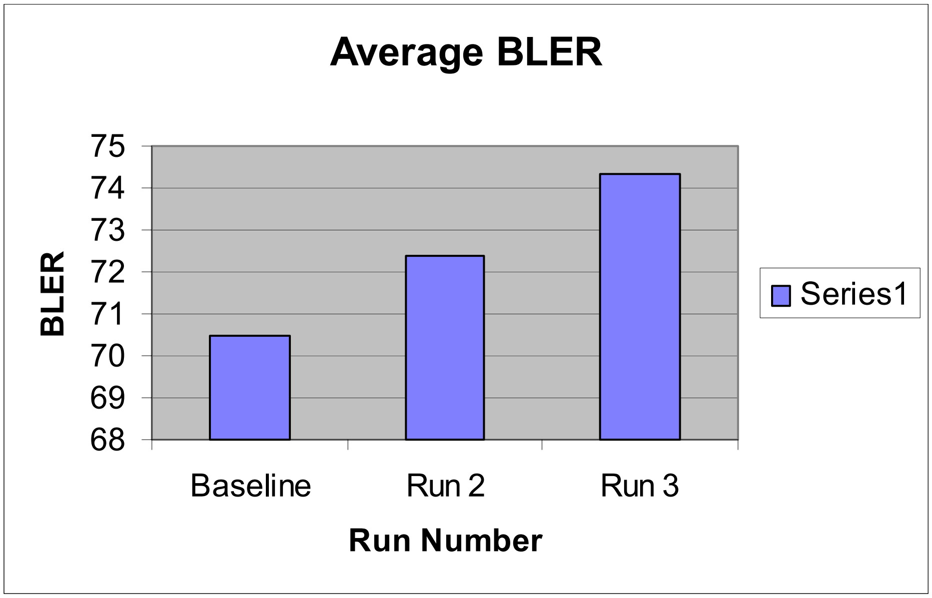

Figure 5. Average BLER for three runs.

Radial noise was also looked at and all CDs were within specification except disc number 68. However, no other parameter was out of specification. A high value of radial noise can occur due to poorly defined pits due to production, surface dirt or scratches, or other factors effecting or interfering with the return signal such as birefringence. Again, the importance of this parameter is only in the comparison with the sample to observe changes and what may be causing errors as they may occur in future years.

Finally, maximum length deviation distributions and maximum jitter distributions on both the land and the pit region are also monitored and is a critical test parameter to indicate the error levels on the CDs. Whenever an E32 error occurs along with high BLER levels, the land length deviation and jitter maximums are out of specification. This gives good correlation with expected results.

The following table tabulates all errors, or parameters above pre-established levels, for all three runs. The numbers represent the number of occurrences the test parameter exceeded the pre-defined level, as a per cent of the total sample. The pre-defined levels are specified in reference 6 and 7. The parameters are summarized in the Appendix.

It is important to note the significant increase in Length Deviation and Jitter in the last run. Length Deviation is the length of each pit and land area measurement compared to the ideal for each time interval, 3T to 11T. Jitter is measured individually for each pit and land 3T to 11T transition. Jitter is measured for the entire track, then calculated and expressed statistically, as a standard deviation.

Bit error can be predicted based on length deviation, signal jitter, and player jitter. Low jitter does not always indicate high quality, but can indicate low average error rates. Jitter does not indicate local defects, such as black spots, birefringence, or scratches.

Type of Measurement	% of CDs out of specification for Baseline	% of CDs out of specification for Run #2	% of CDs out of specification for Run #3
Static Data			
SLD		2.5	
SPD		3.3	2.5
MID		0.8	
SVY	3.3	4.2	4.2
TRP	1.6	4.2	
ECC		0.8	
Vertical Data			
DEV			
DEFL			
PP	8.8	15.8	8.3
PPC	17.6	40	20
XT		0.8	
SVY	12.8	9.2	6.7
Test Data			
BLER	2.4	3.3	4.2
E11	1.6		
E21	0.8		
E31	0.8		0.8
E12	0.8		
E22	11.2		
E32	4.8	4.8	4.8
I3			
I11	2.5	4.2	2.5
I3R			0.8
I11R	1.6	2.5	1.6
REF		3.3	
SYM	1.6	9.2	7.5
BERL	8.8	10.8	13.3
CRC			
RN	4.8	10.8	7.5
Time Interval Data			
Length Deviation		7.5	100*
Jitter	57.6	15	100*

Table 1. Summary of per cent of CDs with out of specification levels for the three runs.

There are other parameters and specific changes to evaluate on a case by case basis. Physical examination using a microscope is also important to look for surface defects or other physical abnormalities.

Accelerated Aging Studies:

Accelerated aging was based on ANSI NPM IT9.21 as described in reference 4. The test conditions are summarized below. Eighty CD-ROMs were used in each batch and the batch is divided into five groups according to the table below. Each group is tested, then placed in the stress chamber for the specified stress time, and re-tested for the BLER and all the other parameters. This process is repeated 4 times until the total soaking time is achieved. The sampling size is sufficient to arrive at a cumulative failure distribution, using the Weibull Distribution, reference 4. The Eyring Model, also reference 4, is then applied to generate a life expectancy for the sample.

Test Condition	Stress Test Time	Total Soaking Time	Number of CDs
80°C @85%RH	500 Hours	2000 Hours	10
80°C @70%RH	500 Hours	2000 Hours	10
80°C @55%RH	500 Hours	2000Hours	15
70°C @85%RH	750 Hours	3000 Hours	15
60°C @85%RH	1000 Hours	4000	30

Table 2. Test conditions for accelerated testing.

The results from these accelerated tests are not complete. Initial stress tests at 80°C at 85%RH are underway. However, after the first 500 hours some significant failure modes have been observed. Under additional stress test these failures seem to become more significant. There are three observable failures. The first are spots appearing on the CD. There is a number of different types of spots, black, white and bubbles, not yet all understood. Some seem to appear on the polycarbonate or reflective surface. Some seem to appear within the surface, and some on the metallized surface, either on the reflective side or causing aberrations on the label side. Image 1a, 1b, and 1,c illustrates consecutive views of a disc with “black spots”. Clearly more work will be undertaken to study the cause and effect of these observations, and try to determine at what temperature they begin to form. In accelerated testing it is always a concern whether the elevated temperature and humidity is destructing the object or just accelerating its aging.

The second failure mode observed is the “disappearing” of the metallized layer. Disappearing in terms of visually. The metallized portion disc basically becomes transparent both to the eye and to the read laser. Image 2 illustrates disappearing of the metallized layer. This occurs at a gradual rate and the illustrated CD seems to be completely deleted.

The third significant failure mode is the pealing back or the flaking off of the metallized layer. Sometimes both are observed as in Image 3. This is not an isolated case, but a rather extreme case. This particular CD was exposed to both hot and cold temperatures. The IT-9 standard does not address cold temperature cycles, but as an experiment this was done just to see what would happen. However other cases have demonstrated the flaking off of the metallized layer in just elevated temperatures. It seems the resin protective layer shrinks and being attached to the metallized layer, peals it off the polycarbonate substrate.

Examples of these three observations, spots, transparency of reflective layer, and pealing and flaking off of metallized later are illustrated in the following images.

To date only CD-ROMs have been subjected to the accelerated testing profile stated above. Plans are underway to include CD-rewritables.

Image 1. Disc showing spots after accelerated aging.

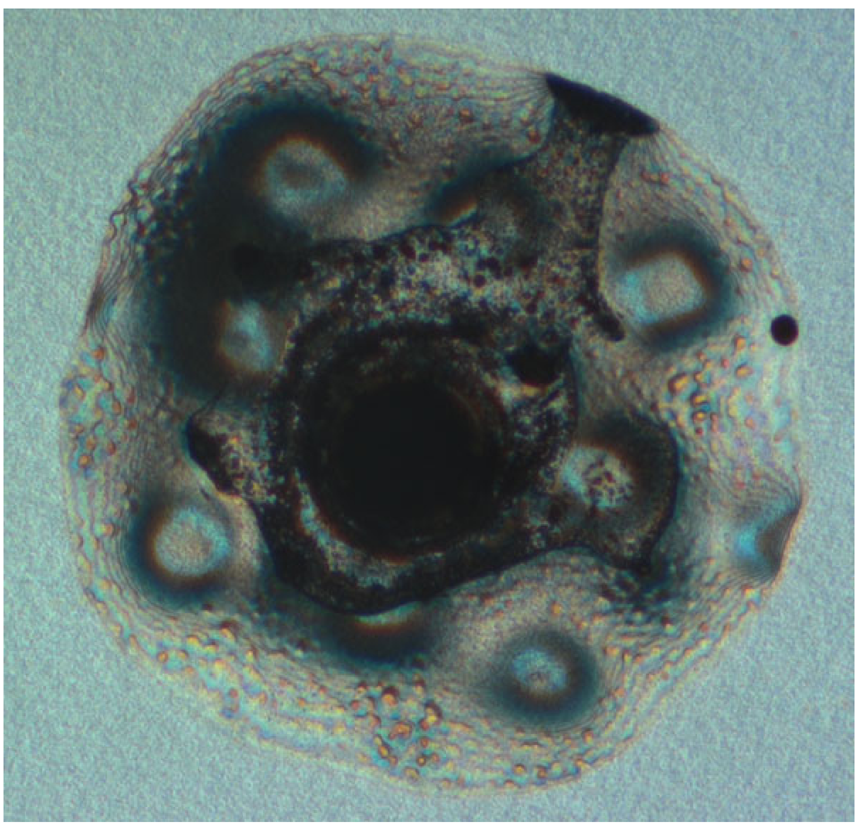

Image 2. Close up of a spot.

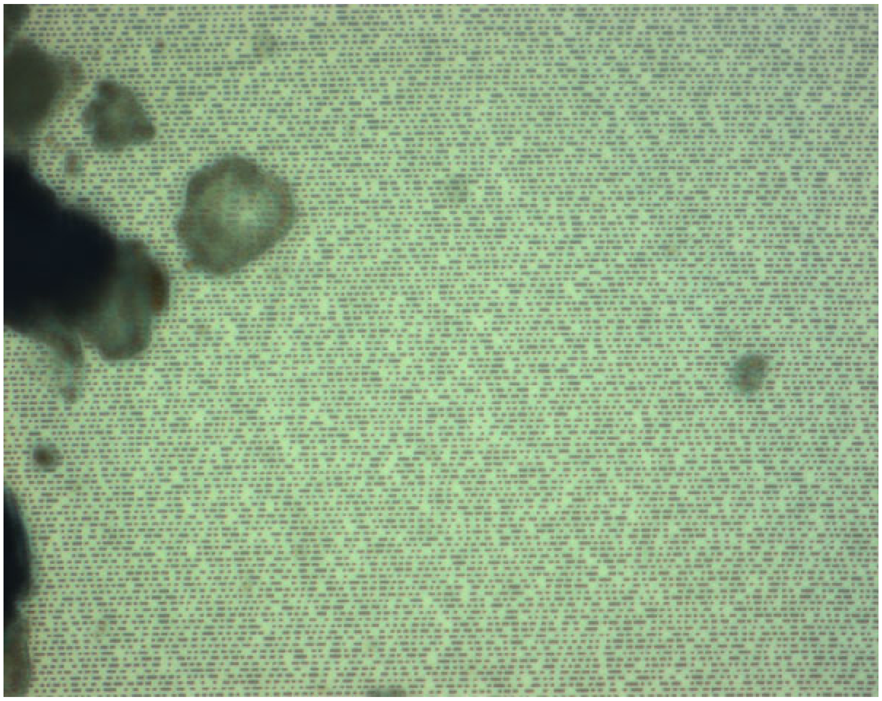

Image 3. Close up showing effect of spot on data.

Image 4. Two CDs one after 500 Hours of accelerated testing.

Image 5. An example of metallized layer pealing and flaking off the polycarbonate substrate.

Conclusions

Although the natural aging pilot project has been in progress for only seven years, the limited data obtained thus far has demonstrated a slight increase in the BLER and a significant increase in the length deviation and jitter measurements. These measurements only cover the CDs in the collection in 1997. Considerable numbers of CDs have been added to the collection which we have no data on. Therefore, it has been discussed to increase the sampling program to include the current CD collection and therefore, increase the sample size from 125 to around 1000, and include CDs manufactured after 1996.

Accelerated aging of CD-ROM (mostly audio) has been time consuming and involves comparing similar manufactured CD’s under different environmental cycles. Efforts are made to obtain identical titles from the same production run in order to have meaningful data. Testing in pairs of 80 CD’s began at 5 aging conditions, but preliminary data indicates it would be best to double the size. Failures have occurred, as shown in the preceding images. Explanations are currently being considered.

Accelerated aging of the CD-R and CD-RW media continues as new media are introduced and manufacturing processes continue to change. These tests are again predominately destructive, involve elevated temperature and humidity “soaks”, but do provide valuable feedback as to modes of failure.

As the CD manufacturing process continues to be perfected, resulting in CDs of lower and lower BLER levels, different material, and improved surface conditions, failure modes will likely also change. Therefore, on going research will be required to maintain some understanding of the longevity and characteristics.

References

1. ANSI X3.199 - 1991 *Information Systems - 365mm (14.0 inch) Optical Disc Cartridge Write Once - Test Method for Media Characteristics.*

2. ANSI AIIM MS59 - 1996 *Media Error Monitoring and Reporting Techniques for Verification of Stored Data on Optical Digital Data Discs*.

3. ANSI AIIM TR39 - 1996 *Guidelines for the Use of Media Error Monitoring and Reporting Techniques for the Verification of Information Stored on Optical Digital Data Discs.*

4. ANSI NPM IT9.21-1996 *Life Expectancy of Compact Discs (CD-ROM) -- Method for Estimating, Based on Effects of Temperature and Relative Humidity*. Similar reports were produced for Magneto-Optical (MO) Discs and CD-R media.

5. CD-CATS Users' Manual, SA3, Audio Development, Inc., www.audiodev.com.

6. *ISO 9660, Information processing – Volume and file structure of CD-ROM for information interchange.*

7. *ISO / IEC 10149, Information technology – Data interchange on read-only 120mm optical data disks (CD-ROM).*

Appendix: Brief Summary of Error Codes

SLD -- Start Lead. In is the optical start of the tracks. This value should be less than 46mm or the TOC (Table of Contents) may be missed.

SPD -- Start of Program. Diameter is used by the player to locate the start of TRK1 (track1).

MID -- Maximum Information Diameter signals the end of the disc. It should be less than 113 mm on a CD-ROM and less than 116 mm on a CD Audio. Handling often gives problems closer to the edge. If it is out of specification, the results may give problems with a weak HF (high frequency) level and disturbed tracking due to birefringence, scratches and fingerprints from handling.

SVY -- Scanning Velocity is the speed with which the pits pass the reading spot.

TRP -- Track Pitch is the distance from the center of one track to the center of the adjacent track.

ECC -- Eccentricity is the measurement of how the geometrical center of the track of information measures with respect to the geometrical center hole of the disc.

DEV -- Deviation specification is + or - 0.5 mm. Deviation which is too high causes focusing problems, which in turn causes loss of the HF signal, higher BLER, and possibly the occurrence of E32s.

DEFL -- Deflection refers to the radial deflection of the light beam due to skew. Deflection + or - 1.6 degrees in the radial direction is the maximum allowable value. Deflection which is too high will result in loss of high frequency (HF) signal.

PP -- Push Pull is the variation in radial noise and is used to translate the wavelength of the noise into an amplitude measurement. Depending how it is measured, either with linear polarized light or with circular polarized light, will vary the results.

PPC -- Push Pull is calculated for circular polarized light from linear polarized light according to Philips measurement correlation data.

XT -- Cross Talk is a measurement for the amount of noise present in the high frequency (HF) signal. XT should be less than 50%. High XT gives garbled HF signal, which in turn gives higher PP readings.

The dynamic test data includes:

BLER -- Block Error Rate is the number of blocks of data that have at least one occurrence of erroneous data (E11 + E21 + E31). BLER is quantified as the rate of errors per second. BLER is critical because the errors need to be kept at the minimum to insure data integrity.

E11 -- E11 indicates how the existing errors are divided into different severity's. Measured in counts per second, E11 indicates the occurrence of single symbol correctable errors.

E21 -- E21 indicates how the existing errors are divided into different severity's. Measured in counts per second, E21 indicates the occurrence of double symbol correctable errors.

E31 -- E31 indicates how the existing errors are divided into different severity's. Measured in counts per second, E31 indicates the number of first decoder (C1) uncorrectable errors.

E12 -- E12 indicates the occurrence of single symbol correctable error in the second decoder (C2), measured in counts per second. As E31 errors penetrate to the second decoder, such errors can be further investigated by monitoring the E12, E22, and E32 readings. A high level of E12 is not significant, because one single E31 count can contain up to 30 E12 single symbol correctable errors, as resulting of interleaving.

E22 -- E22 is a two symbol correctable error in the second decoder (C2) caused either by one big error or a very high degree of cluster errors. If E22 exists at all, the disc is approaching uncorrectable errors, and there is not much margin of error left to the user.

E32 -- E32 indicates uncorrectable errors in the C2 decoder or the existence of unreadable data on the disc. E32 should never be present on a CD.

I3 -- I3 is the HF level of the shortest pits and land areas of the disc. The I3 level should be kept between 0.3 and 0.7. I3 should never fall below 0.3 and should preferable be kept above 0.35. Maintaining this level on discs of more than 70 minutes is difficult. I3 levels which are too low result in decoding problems. Scratches and fingerprints from handling give a weak I3 level. I3 is measured by comparing levels with those on a reference disc having known values.

I11 -- I11 is the HF level of the longest pits and land areas of the disc. I11 should be kept able 0.6. I11 levels which are too low result in decoding problems. I11 is measured by comparing levels with those on a reference disc having known values.

I3R and I11R -- I3R and I11R are the ratios of I3 and I11 by the maximum. I3R and I11R measurements make it possible to distinguish between amplitude variations caused by pit deformation and amplitude variations caused by absorption in substratum and reflective layer. Measurements are normalized by the reflectivity. I3R and I11R make it possible to see if there are still good pits even though the signal level is low.

REF -- Reflectivity is calibrated with a good reference disc and is used for detection of reflection variations and normalization of I3R and I11R. Reflectivity is normalized by dividing the maximum level by 0.95.

SYM -- Symmetry is given as an absolute value. Specifications for SYM is less than 20% for CD Audio discs. It should be less than 10% for a CD-ROM. SYM which is too high results in decoder level slicer problems, which would give a BLER reading that would be too high.

BERL -- Burst Error Length measurement counts the number of consecutive C2 blocks in error, normally indicating physical damage. Like E22, high BERL leaves little room for error, i.e., handling, dirt or scratches, after the disc is in use. BERL is important because it indicates the presence of a physical defect large enough to impact more than one block of data.

CRC -- Cyclic Redundancy Check shows the number of blocks per second, where CRC error are detected. CRC is made on the subcode information.

RN -- Radial Noise has a limit of 30 nanometers within the bandwidth of 500 to 2500 Hz. RN occurs when tracks are damaged. High RN peaks causes the servo to skip tracks. High average RN is an indication of poorly defined pits (worn down stamper or mastering problem).

BEGL -- Burst Errors Greater than Limits where the limit is set to 7. This measurement counts the number of occurrences when there were 7 or more blocks in error.

E32TOT -- This measurement counts the total number of uncorrectable blocks present within the testing time. This number should be “0”.

The time interval data includes:

Length deviation -- The length of each pit and land area is measured and compared to the ideal pit and land lengths. The result is compared for each run length, 3T to 11T, (9 values) with variations preset for each run length.

Jitter -- Jitter is measured individually for pit and land (3T ...11T), 9 times 2 (18) measurements. Each pit and land is measured and then jitter is calculated statistically as a standard deviation, (18 more measurements) according to Philips specifications. This is done for the entire track of the disc. Jitter is the imprecision in the timing of the discrete samples, pit and land transition, when converting from analog to digital or digital to analog. It involves the tracking, timing of synchronous clock, and any imperfections on the disc. In general this measurement is a good indication of overall disc data quality.